Bottom-Up Energy Modeling
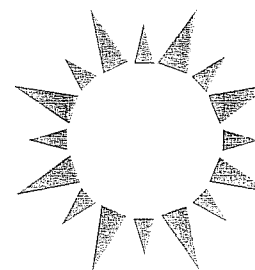
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Glossary

base year The year for which the inventory is to be taken. In some cases (such as estimating CH_4 from rich production), the base year is simply the last year of a number of years over which an average must be taken.

bottom-up modeling A modeling approach that arrives at economic conclusions from an analysis of the effect of changes in specific parameters on narrow parts of the total system.

carbon tax A tax on fossil fuels based on the individual carbon content of each fuel. Under a carbon tax, coal would be taxed the highest per MBtu, followed by petroleum and then natural gas.

demand-side management The planning, implementation, and monitoring of utility activities designed to encourage customers to modify their pattern of electricity usage.

discount rate The rate at which money grows in value (relative to inflation) if it is invested.

dynamic In the field of modeling, a dynamic model includes intertemporal relations between variables. A model that does not include such relations is called static.

energy forms and levels Primary energy is energy that has not been subjected to any conversion or transformation process. Secondary energy (derived energy) has been produced by the conversion or transformation of primary energy or of another secondary form of energy. Final energy (energy supplied) is the energy made available to the consumer before its final conversion (i.e., before utilization). Useful energy is the energy made usefully available to the consumer after its final conversion (i.e., in its final utilization).

energy intensity The amount of energy required per unit of a particular product or activity.

energy services The service or end use ultimately provided by energy. For example, in a home with an electric heat pump, the service provided by electricity is not to drive the heat pump's electric motor but rather to provide comfortable conditions inside the house.

engineering approach A particular form of bottom-up modeling in which engineering-type process descriptions (e.g., fuel efficiency of end-use devices) are used to calculate a more aggregated energy demand. This term is particularly used in contrast to econometric models.

exogenous variables Variables determined outside the system under consideration. In the case of energy planning models, these may be political, social, or environmental, for example.

feedback When one variable in a system (e.g., increasing temperature) triggers changes in a second variable (e.g., cloud cover), which in turn ultimately affects the original variable (i.e., augmenting or diminishing the warming). A positive feedback intensifies the effect. A negative feedback reduces the effect.

fossil fuel Coal, petroleum, or natural gas or any fuel derived from them.

general equilibrium analysis An approach that considers simultaneously all the markets in an economy, allowing for feedback effects between individual markets. It is particularly concerned with the conditions that permit simultaneously equilibrium in all markets and with the determinants and properties of such an economy-wide set of equilibrium.

income elasticity The expected percentage change in the quantity demand for a good given a 1% change in income. An income elasticity of demand for electricity of 1.0 implies that a 1% increase in income will result in a 1% increase in demand for electricity.

input-output analysis A method of investigating the interrelationship between the branches of a national economy in a specific time period. The representation, in the form of a matrix table, is called an input-output table. An input-output analysis allows the changes in total demand in related industrial branches to be estimated.

least-cost planning In energy planning, the practice of basing investment decisions on the least costly option

for providing energy services. It is distinguished from the more traditional approach taken by utilities, which focuses on the least costly way to provide specific types of energy, with little or no consideration of less costly alternatives that provide the same energy service at lower costs.

linear programming A practical technique for finding the arrangement of activities that maximizes or minimizes a defined criterion subject to the operative constraints. For example, it can be used to find the most profitable set of outputs that can be produced from a given type of crude oil input to a given refinery with given output prices. The technique can deal only with situations where activities can be expressed in the form of linear equalities or inequalities and where the criterion is also linear.

macroeconomics The study of economic aggregates and the relationships between them. The targets of macro-economic policy are the level and rate of change of national income (i.e., economic growth), the level of unemployment, and the rate of inflation. In macro-economics, the questions about energy are how its price and availability affect economic growth, unemployment, and inflation, and how economic growth affects the demand for energy.

marginal costs In linear programming, this term has the very specific meaning of change of the objective function value as a result of a change in the right-hand-side value of a constraint. If, for example, the objective is to minimize costs, and if the capacity of a particular energy conversion facility, such as a power plant, is fully utilized, the marginal cost in the linear planning sense expresses the (hypothetical) reduction of the objective function value (i.e., the benefit) of an additional unit of capacity.

market clearing The economic condition of supply equaling demand.

optimization model A model describing a system or problem in such a way that the application of rigorous analytical procedures to the representation results in the best solution for a given variable(s) within the constraints of all relevant limitations.

price elasticities The expected percentage change in quantity demand for a good given a 1% change in price. A price elasticity of demand for electricity of -0.5 implies that a 1% increase in price will result in a half percent decrease in demand for electricity.

renewable energy Energy obtained from sources that are essentially inexhaustible (unlike, for example, the fossil fuels, of which there is a finite supply). Renewable sources of energy include wood, waste, wind, geothermal, and solar thermal energy.

retrofit To update an existing structure or technology by modifying it, as opposed to creating something entirely new from scratch. For example, an old house can be retrofitted with advanced windows to slow the flow of energy into or from the house.

scenario Coherent and plausible combination of hypotheses, systematically combined, concerning the exogenous variables of a forecast.

sensitivity analysis A method of analysis that introduces variations into a model's explanatory variables to examine their effects on the explained.

simulation model Descriptive model based on a logical representation of a system and aimed at reproducing a simplified operation of this system. A simulation model is referred to as static if it represents the operation of the system in a single time period; it is referred to as dynamic if the output of the current period is affected by evolution or expansion compared with previous periods. The importance of these models derives from the impossibility of excessive cost of conducting experiments on the system itself.

top-down modeling A modeling approach that proceeds from broad, highly aggregated generalizations to regionally or functionally disaggregated details.

Two general approaches have been used for the integrated assessment of energy demand and supply: the so-called bottom-up and top-down approaches. The bottom-up approach focuses on individual technologies for delivering energy services, such as household durable goods and industrial process technologies. For such technologies, the approach attempts to estimate the costs and benefits associated with investments in increased energy efficiency, often in the context of reductions in greenhouse gas (GHG) emission or other environmental impacts. The top-down method assumes a general equilibrium or macroeconomic perspective, wherein costs are defined in terms of losses in economic output, income, or gross domestic product (GDP), typically from the imposition of energy or emissions taxes.

1. GOALS, CONTEXT, AND USE: BOTTOM-UP APPROACHES

The fundamental difference between the two approaches is in the perspective taken by each on consumer and firm behavior and the performance of markets for energy efficiency. The bottom-up approach assumes that various market "barriers" prevent consumers from taking actions that would be in their private self-interest—that is, would result in the provision of energy services at lower cost. These market barriers include lack of information about energy efficiency opportunities, lack of access to capital to finance energy efficiency investment, and misplaced incentives that separate responsibilities

for making capital investments and paying operating costs. In contrast, the top-down approach generally assumes that consumers and firms correctly perceive, and act in, their private self-interest (are utility and profit maximizers) and that unregulated markets serve to deliver optimal investments in energy efficiency as a function of prevailing prices. In this view, any market inefficiencies pertaining to energy efficiency result solely from the presence of environmental externalities that are not reflected in market prices.

In general, an assessment carried out using the bottom-up approach will very likely show significantly lower costs for meeting a given objective (e.g., a limit on carbon emissions) than will one using a top-down approach. To some extent, the differences may lie in a failure of bottom-up studies to accurately account for all costs associated with implementing specific actions. Top-down methods, on the other hand, can fail to account realistically for consumer and producer behavior by relying too heavily on aggregate data, as noted by Krause *et al.* In addition, some top-down methods sacrifice sectoral and technology detail in return for being able to solve for general equilibrium resource allocations. Finally, Boero *et al.* noted that top-down methods often ignore the fact that economies depart significantly from the stylized equilibria represented by the methods. Each approach, however, captures costs or details on technologies, consumer behavior, or impacts that the other does not. Consequently, a comprehensive assessment should combine elements of each approach to ensure that all relevant costs and impacts are accounted for.

The two approaches have been used in the development of national energy plans or policies that require identification and analysis of different actions that governments could take to encourage adoption of energy technologies and practices. Based on such analyses, policymakers can decide which options not only satisfy specific policy objectives but are also within institutional, political, and budget constraints. Typically, the analytic process will follow a series of steps, each of which produces information for decision makers. The manner in which these steps are performed will reflect each country's resources, objectives, and decision-making process.

Both approaches have been used extensively in the assessment of costs of climate change mitigation. The earlier literature dating to 1970s focused primarily on evaluation of the energy and particularly the petroleum sector, and categorized approaches into sectoral models, industry-market models, energy system models, and energy economy models. The first three approaches would be referred to as bottom-up approaches and the last one as the top-down approach today. From the late 1980s to date, much of the attention in the application of these two energy-sector approaches has focused on climate change mitigation, that is, the long-term stabilization of climate change and the short-term reduction of GHG emissions. The following sections focus on the evolution and use of energy-sector bottom-up approaches as they have been applied for mitigation assessment, particularly the short-term reduction of GHG emissions.

2. STRUCTURE OF AN ENERGY SECTOR BOTTOM-UP ASSESSMENT

The energy sector comprises the major energy demand sectors (industry, residential and commercial, transport, and agriculture) and the energy supply sector (resource extraction, conversion, and delivery of energy products). GHG emissions occur at various points in the sector, from resource extraction to end use, and, accordingly, options for mitigation exist at various points.

The bottom-up approach involves the development of scenarios based on energy end uses and evaluation of specific technologies that can satisfy demands for energy services. One can compare technologies based on their relative cost to achieve a unit of GHG reduction and other features of interest. This approach gives equal weight to both energy supply and energy demand options. A variety of screening criteria, including indicators of cost-effectiveness as well as noneconomic concerns, can be used to identify and assess promising options, which can then be combined to create one or more mitigation scenarios. Mitigation scenarios are evaluated against the backdrop of a baseline scenario, which simulates the events assumed to take place in the absence of mitigation efforts. Mitigation scenarios can be designed to meet specific emission reduction targets or to simulate the effect of specific policy interventions. The results of a bottom-up assessment can then be linked to a top-down analysis of the impacts of energy sector scenarios on the macroeconomy.

Energy-sector bottom-up assessments require physical and economic data about the energy system, socioeconomic variables, and specific technology options, and GHG emissions if these are targeted. Using these data, a model or accounting system of the energy sector is designed to suit local circumstances.

The manner in which an assessment is performed reflects each country's resources, objectives, and decision-making process as well as the type of modeling approach employed. Figure 1 depicts the basic steps of a typical mitigation assessment and how they relate to one another. Some of the steps are interlinked, so they are not necessarily sequential, and require iterations.

An initial step is to assemble data for the base year on energy demand by sector, energy supply by type of energy source, and energy imports and exports. The disaggregated energy data is normalized to match the national energy supply totals for the base year. One then calibrates base year emissions with the existing GHG inventory, as needed. The analyst also assembles data for the base year on the technologies used in end-use sectors and in energy supply.

The data for the base year is used as a starting point for making projections of future parameters and developing integrated scenarios of energy demand and supply. On both the demand and supply side, one identifies and screens potential technology options to select those that will be included in the analysis. The screening is guided by information from an assessment of energy resources, as well as the potential for energy imports and exports.

Once the list of technologies has been made manageable by the screening process, the analyst characterizes potential technology options in end-use sectors and in energy supply with respect to costs, performance, and other features. On the demand side, this characterization will assist in projecting end-use energy demands in the various sectors. Projecting energy demand also requires one to project activity levels in each subsector for indicators such as tons of various industrial products, demand for travel and freight transport, and number of urban and rural households. These projections are based on the assumptions for growth in key parameters such as GDP and population. Assumptions about sectoral policies with respect to energy pricing and other factors are also important in developing projections of energy demand.

The data from the energy demand and supply analyses are then entered into an energy sector model or accounting framework that allows for integrated analysis of the various options that can meet energy requirements. This analysis calculates costs and impacts over the time horizon considered, the results are reviewed for reasonableness, and uncertainty is taken into consideration. This step involves combining technology options to meet the objectives of each scenario. The selection of technologies may be made directly by the analyst or performed by the model (as with an optimization model).

The baseline scenario projects energy use and emissions over the time horizon selected, reflecting the development of the national economy and energy system under the assumption that no policies are introduced to reduce GHG emissions. The baseline scenario must include sufficient detail on future energy use patterns, energy production systems, and technology choices to enable the evaluation of specific policy options. An alternative baseline
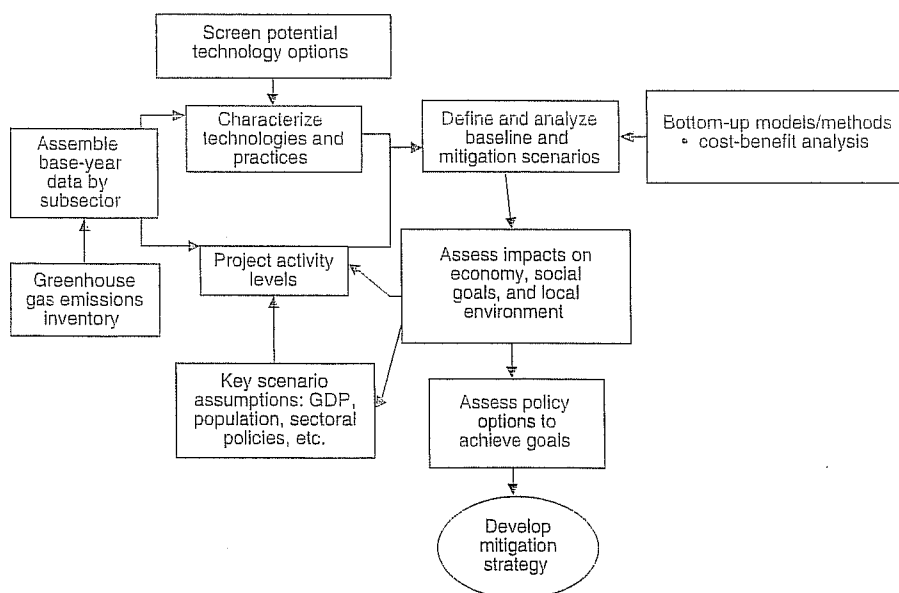

FIGURE 1   Structure of a bottom-up assessment.

scenario can be developed if desired (for example, to reflect different assumptions about GDP growth).

Policy scenarios can be defined to meet particular emission reduction targets, to assess the potential impact of particular policies or technologies, or to meet other objectives. The comparisons of policy and baseline scenarios reveal the net costs and impacts of the policy options. The results are assessed with respect to reasonableness and achievability, given barriers to implementation and the policy instruments that might be used, such as taxes, standards, or incentive programs.

For both baseline and policy scenarios, the analyst assesses the impacts on the macroeconomy, social goals (such as employment), and the national environment. One approach is to integrate bottom-up assessment with a macroeconomic model. Decision analysis methods that allow for consideration of multiple criteria may also be appropriate.

After scenarios have been analyzed and options have been ranked in terms of their attractiveness (on both quantitative and qualitative terms), it is desirable to conduct a more detailed evaluation of policies that can encourage adoption of selected options. Such an evaluation can play an important role in the development of a national strategy. The latter step requires close communication between analysts, policymakers, and other interested parties.

3. TYPICAL MODELS FOR A BOTTOM-UP ENERGY SECTOR ASSESSMENT

Bottom-up assessments of the energy sector typically use an accounting or modeling framework to capture the interactions among technologies and to ensure consistency in the assessment of energy, emission, and cost impacts. Accounting and modeling methods can vary greatly in terms of their sophistication, data intensiveness, and complexity. This section provides an overview of key concepts and capabilities of some models that have been used for this purpose in energy/environmental studies in developing and industrialized countries.

As discussed earlier, it is common to divide energy models into two types, so-called bottom-up and top-down, depending on their representation of technology, markets, and decision making. In practice, there is a continuum of models, each combining technological and economic elements in different ways. At one extreme are pure bottom-up energy models, which focus on fuels and energy conversion or end-use technologies and treat the rest of the economy in an aggregated fashion. At the other extreme are pure top-down models, which treat energy markets and technologies in an aggregated manner and focus instead on economy-wide supply-demand relations and optimizing behavior. Between these two cases are a number of models that combine elements of both extremes with various degrees of emphasis and detail.

The description of the future varies among the models. Some models can only analyze a snapshot year and compare this to another year, without any representation of the transition between them. Dynamic models, on the other hand, allow for time-dependent descriptions of the different elements of the energy system. While the snapshot models enable great detail in the representation of the system, dynamic models allow for representation of technology capacity transfer between time periods and thus time-dependent capacity expansion, time-dependent depletion of resources, and abatement costs as they vary over time.

In dynamic modeling, information about future costs and prices of energy is available through two diametrically different foresight assumptions. With myopic foresight, the decisions in the model are made on a year-by-year basis, reflecting the assumption that actors expect current prices to prevail indefinitely. Assuming perfect foresight, the decisions at any year are based on the data for the entire time horizon. The model thus reflects the activities of market participants as if they use the model itself to predict prices.

Table I summarizes the key design features of some of the models. Most of the models listed in Table I can be used to integrate data on energy demand and supply. The models can use this information for determining an optimal or equilibrium mix of energy supply and demand options. The various models use cost information to different degrees and provide for different levels of integration between the energy sector and the overall economy.

3.1 Energy Accounting Models

Energy accounting models reflect an engineering or input-output conception of the relations among energy, technology, and the services they combine to produce. This view is based on the concept of energy services that are demanded by end users. Schematically, this can be represented as follows:

Energy inputs > Technology > Energy services.

TABLE I

Key Design Features of Types of Bottom-Up Energy Sector Models

Model characteristics	Energy accounting	Engineering optimization	Iterative equilibrium	Hybrid
Energy supply representation	Process analysis	Process analysis	Supply curve	Process analysis
Energy demand representation	Exogenous	Exogenous	Exogenous	Utility maximization
Multiperiod	Yes	Yes	Yes	Yes
Consumer/producer foresight	Not applicable	Perfect/myopic	Myopic	Perfect/myopic
Solution algorithm	Accounting	Linear or nonlinear optimization	Iteration	Nonlinear optimization

For policy purposes, the significance of this approach is that a given type and level of energy service can be obtained through various combinations of energy inputs and technologies. In particular, holding the service constant while increasing the energy efficiency of the technology allows decrease in the required level of energy input. In a range of cases, when other factors are held equal, this lowers the overall cost of the energy service. With accounting models, the evaluation and comparison of policies is performed by the analyst external to the model itself.

These models are essentially elaborations on the following accounting identity describing the energy required for satisfying a given level of a specific energy service:

$$E = AI,$$

where E indicates energy, A indicates activity, and I indicates intensity. With multiple end uses, aggregate energy demand is simply the sum as follows:

$$E = \text{Sum of } (A_i I_i).$$

Accounting models are essentially spreadsheet programs in which energy flows and related information such as carbon emissions are tracked through such identities. The interpretation of the results, and the ranking of different policies quantified in this manner, is external to the model and relies primarily on the judgment of the analyst.

Note that these calculations assume that a number of factors are held constant, including energy service level and equipment saturations. Also, these expressions represent a quasi-static view; in actual practice, such calculations would be performed over time paths of costs, activities, intensities, and prices developed in scenario construction. Finally, it is easy to see that factors for carbon savings from the shift to efficient technologies can be easily included in such calculations.

In energy accounting models, macroeconomic factors enter only as inputs in deriving demand-side projections—that is, there is no explicit representation of feedback from the energy sector to the overall economy. While different models contain different levels of detail in representing the supply sector, supply-demand balancing in this type of model is accomplished by back calculation of supply from demand projections.

In contrast to optimization models, accounting models cannot easily generate a least-cost mitigation solution. They can be used to represent cost-minimizing behavior estimated by the analyst, however. They tend to require less data and expertise and are simpler and easier to use than optimization models.

3.2 Engineering Optimization Models

In engineering optimization models, the model itself provides a numerical assessment and comparison of different policies. These models are linear programs in which the most basic criterion is total cost of providing economy-wide energy services under different scenarios; when this criterion is used, the structure of this type of model as used in mitigation analysis can be represented schematically as follows:

Minimize total cost of providing energy

and satisfying end-use demand subject to

1. Energy supplied, energy demanded
2. End-use demands satisfied
3. Available resource limits not exceeded

In addition to the overall optimization structure of these models, perhaps the key distinction between these and the accounting models is that, within the model structure itself, trade-offs are made among different means of satisfying given end-use demands for energy services.

The intertemporal structure of these linear programming models varies. Some are constructed to perform a target year analysis: the model is

first parameterized and run for the base year, then the procedure is repeated for a single designated future year (typically 2005, 2010, or 2020). Others perform a more elaborate dynamic optimization, in which time paths of the parameters are incorporated and the model generates time paths of solutions.

In engineering optimization models, macroeconomic factors enter in two ways. First, they are used to construct forecasts of useful energy demands. Second, they can be introduced as constraints. For example, the overall cost minimization can be constrained by limits on foreign exchange or capital resources. In both cases, the models do not provide for the representation of feedbacks from the energy sector to the overall economy.

Supply and demand are balanced in engineering optimization models by the presence of constraints, as indicated earlier. The engineering detail and level of disaggregation used in both the supply and demand side are at the discretion of the user, and in practice these vary widely among models.

This type of model allows several means of analyzing GHG emissions and the effects thereupon of various policy options. For example, as an alternative to minimizing energy costs, criteria such as minimizing carbon output subject to the constraints can be employed. In addition, an overall cap on carbon emissions can be entered as a constraint in the model and the cost minimization performed with this restriction. Each such approach allows the comparison of different policy intervention.

3.3 Iterative Equilibrium Models

These models incorporate the dynamics of market processes related to energy via an explicit representation of market equilibrium—that is, the balancing of supply and demand. These are used to model a country's total energy system and do not explicitly include an economy model integrated with the energy system model. Thus, macroeconomic factors enter the model exogenously, as in the previous model types discussed. (That is, demands for energy services are derived from macroeconomic drivers rather than being obtained endogenously.) These models thus occupy an intermediate position between engineering, energy-focused models, and pure market equilibrium models.

The methodology employed to solve the model is a process network wherein individual energy processes are represented with standard model forms, with application specific data, and linked together as appropriate. Prices and quantities are then adjusted iteratively until equilibrium is achieved. This iterative approach makes it much easier to include noncompetitive-market factors in the system than in the optimization approach.

3.4 Hybrid Models

In hybrid models, the basic policy measure is the maximization of the present value of the utility of a representative consumer through the model planning horizon. Constraints are of two types: macroeconomic relations among capital, labor, and forms of energy, and energy system constraints. The model generates different time paths of energy use and costs and macroeconomic investment and output. The energy submodel contains representations of end-use technologies, with different models containing different levels of detail. Schematically, this type of model can be represented as follows:

Maximize (discounted) utility of consumption

    subject to

1. Macroeconomic relations among output, investment, capital, labor, and energy
2. Energy system and resource constraints (as in engineering optimization models)

The constraints in this case are also dynamic: they represent time paths for the model variables.

In this type of model, energy demands are endogenous to the model rather than imposed exogenously by the analyst. In addition, this optimization structure indicates the difference we noted earlier in the way the different models incorporate macroeconomic data. Specifically, in accounting and engineering optimization models, these data—on GDP, population growth, capital resources, and so on—enter essentially in the underlying constructions of the baseline and policy scenarios. In the hybrid model, however, such data enter in the macroeconomic relations (technically, the aggregate production function) as elasticities and other parameters. Within this model framework, changes in energy demand and supply can feed back to affect macroeconomic factors. It should be noted that, despite their inclusion of engineering optimization subcomponents, these models typically do not contain as much detail on specific end-use technologies as many purely engineering models.

4. KEY CHALLENGES IN THE BOTTOM-UP MODELING APPROACH

A number of key challenges arise in the bottom-up modeling approach. These include (1) incorporating efficiency versus equity; (2) aggregation over time, regions, sectors, and consumers; (3) representing decision rules used by consumers; (4) incorporating technical change; (5) capturing facility retirement dynamics; (6) avoiding extreme solutions; and (7) accounting for carbon flows.

4.1 Incorporating Efficiency versus Equity

None of the models discussed earlier provide explicitly for making trade-offs between efficiency and equity. Different models, however, have different implications for the analyst's consideration of this important issue. Nonoptimization models do not themselves choose among different policies in an explicit way but can allow for the ranking of policies according to criteria specified by the analyst, including considerations of equity. Engineering optimization models, since they focus on least-cost solutions to the provision of energy services, leave to the analyst the judgment of how to trade-off the importance of energy with that of other economic and social priorities. The models that optimize the utility of a representative consumer, in a sense, constrain consideration of the issue the most. Embedded in this modeling structure is a view of the economic system that equates social optima with competitive economic equilibria; the appropriateness of this perspective in the application at hand must be weighed carefully.

4.2 Aggregation over Time, Regions, Sectors, and Consumers

Perhaps the most fundamental formulation issue is the level of aggregation at which costs and benefits are calculated. Economic efficiency is generally insured if discounted net benefits are maximized in the aggregate; any desired income redistribution is handled subsequently. Decision makers, however, are fundamentally interested in how the costs and benefits fall on various income, industry, and regional groups. Coupled with the relative emphasis of the analysis on equity versus efficiency is the desired level of disaggregation of the model by region, time periods, industry, and income group.

Obviously, the level of disaggregation must be sufficient to allow reporting of results at the desired level, but in some cases the projection of an aggregate variable can be improved by some level of disaggregation to capture the heterogeneity in decision making objects on the part of the different groups. These decision rules themselves are critical elements of the models and range from minimizing discounted future costs (or maximizing benefits) over a 40- or 50-year time horizon to picking investments that come close to minimizing costs based on conditions for a single year only.

4.3 Representing Decision Rules Used by Consumers

Accounting models contain no explicit representation of consumer decision making. In practice, however, their use often reflects the view that certain market barriers constrain consumers from making optimal decisions with respect to energy efficiency. At the other extreme, the use of the representative consumer in the optimization models rests on strong assumptions regarding consumer behavior, serving primarily to ensure mathematical and empirical tractability. Key among these are perfect foresight and essential homogeneity among consumers or households.

4.4 Incorporating Technical Change

Another set of key assumptions about inputs are those made about the costs and efficiencies of current and future technologies, both for energy supply and energy use. Most analysts use a combination of statistical analysis of historical data on the demand for individual fuels and a process analysis of individual technologies in use or under development to represent trends in energy technologies. At some point these two approaches tend to look quite similar though, as the end-use process analysis usually runs out of new technology concepts after some years or decades, and it is then assumed that the efficiency of the most efficient technologies for which there is an actual proposed design will continue to improve as time goes on. Particularly important, but difficult, here is projecting technological progress. Almost all top-down models have relied on the assumption of "exogenous" or "autonomous" technical change, that is, productivity trends (relating to energy as well as other factors of production) that are a function of time only, and in particular not affected by either changes in relative factor prices or by policy

interventions. Bottom-up approaches, by contrast, assume (usually implicitly) that technological progress can be accelerated by policy intervention. This difference constitutes another significant contrast between the two approaches. There has been an acceleration of research, among top-down modelers, on incorporating technological change that is "endogenous"—that is, responsive to price changes, policies, or both. This research may eventually contribute to a partial reconciliation of the two approaches in the treatment of technological progress.

4.5 Capturing Facility Retirement Dynamics

Most modeling approaches focus on investments in new energy producing and consuming equipment, which is typically assumed to have a fixed useful lifetime. In scenarios where conditions change significantly (either through external factors or explicit policy initiatives), it may be economic to retire facilities earlier or later than dictated purely by physical depreciation rates. This endogenous calculation of facility retirement dates can be handled analytically in most models, but it represents a major increase in data and computational requirements.

4.6 Avoiding Extreme Solutions

Another typical problem, particularly with models that assume optimizing behavior on the part of individual economic agents, is the danger of knife edge results, where a small difference in the cost of two competing technologies can lead to picking the cheaper one only. This is generally handled by disaggregating consumers into different groups who see somewhat different prices for the same technology (e.g., coal is cheaper in the coal fields than a thousand miles away), modeling the decision process as somewhat less than perfect, or building appropriate time lags into the modeling structure.

4.7 Accounting for Carbon Flows

Finally, estimating carbon flows for a given energy system configuration can be complicated. It is more accurate to measure emissions as close to the point of combustion as possible so types of coal and oil product can be distinguished and feedstocks (which do not necessarily produce carbon emissions) can be netted out. However, a point-of-use model requires far more data and computation than the models described here, which aggregate several fuel types and use average carbon emissions factors for each fossil fuel.

5. DATA SOURCES FOR BOTTOM-UP ANALYSIS

Regardless of the approach taken and analysis tool used, the collection of reliable data is a major and relatively time-consuming aspect of bottom-up analysis. To keep data constraints from becoming a serious obstacle to the analysis, two points are essential. First, the bottom-up model should be sufficiently flexible to adapt to local data constraints. Second, the data collection process should be as efficient as possible. Efficiency can be maximized by focusing the detailed analysis on sectors and end uses, where the potential for GHG mitigation is most significant, and avoiding detailed data collection and analysis in other sectors.

Data collection generally begins with the aggregate annual energy use and production figures typically found on a national energy balance sheet. The remaining data requirements depend largely on (1) the disaggregated structure of the analysis, (2) the specific technology and policy options considered, and (3) local conditions and priorities.

Table II shows the typical types of data needed for a bottom-up approach to mitigation analysis. They tend to fall within five general categories: macroeconomic and socioeconomic data, energy demand data, energy supply data, technology data, and emission factor data. The full listing of potential data requirements may appear rather daunting. In practice, however, much of the data needed may already be available in the form of national statistics, existing analytical tools, and data developed for previous energy sector studies. The development and agreement on baseline projections of key variables, the characterization of mitigation options relevant to local conditions, and, if not already available, the compilation of disaggregated energy demand data are typically the most challenging data collection tasks facing the analyst.

In general, emphasis should be placed on locally derived data. The primary data sources for most assessments will be existing energy balances, industry-specific studies, household energy surveys, electric utility company data on customer load profiles, oil company data on fuel supply, historical fuel price series maintained by government departments, vehicle statistics kept by the transportation department,

TABLE II

Data Sources for a Bottom-Up Mitigation Analysis

Data categories	Types of data	Common data sources
Macroeconomic variables		
Aggregate driving variables	GDP/value added, population, household size	National statistics and plans; macroeconomic studies
More detailed driving variables	Physical production for energy intensive materials; transportation requirements; agricultural production and irrigated area; changes in income distribution, etc.	Macroeconomic studies; transport sector studies; household surveys, etc.
Energy demand		
Sector and subsector totals	Fuel use by sector/subsector	National energy statistics, national energy balance, energy sector yearbooks (oil, electricity, coal, etc.)
End-use and technology characteristics by sector/subsector	Energy consumption breakdown by enduse and device: e.g., energy use characteristics of new versus existing building stock; vehicle stock; breakdown by type, vintage, and efficiencies; or simpler breakdowns	Local energy studies; surveys and audits; studies in similar countries; general rules of thumb from end-use literature
Response to price and income changes (optional)	Price and income elasticities	Local econometric analyses; energy economics literature
Energy supply		
Characteristics of energy supply, transport, and conversion facilities	Capital and O&M costs, performance (efficiencies, unit intensities, capacity factors, etc.)	Local data, project engineering estimates, Technical Assessment Guide; IPCC Technology Characterization Inventory
Energy prices		Local utility or government projections; for globally traded energy products
Energy supply plans	New capacity online dates, costs, characteristics	National energy plans; electric utility plans or projections; other energy sector industries (refineries, coal companies, etc.)
Energy resources	Estimated, proven recoverable reserves of fossil fuels; estimated costs and potential for renewable resources	Local energy studies
Technology options		
Technology costs and performance	Capital and O&M costs, performance (efficiencies, unit intensities, capacity factors, etc.)	Local energy studies and project engineering estimates; technology suppliers; other mitigation studies
Penetration rates	Percent of new or existing stock replaced per year; overall limits to achievable potential	
Emission factors	Kg GHG emitted per unit of energy consumed, produced, or transported	National inventory assessments; IPCC Inventory Guidelines IPCC Technology Characterization Inventory

and so on. The main thrust of the data collection effort is not so much on collecting new primary data but on collating secondary data and establishing a consistent data set suitable for analysis using the model of choice.

Where unavailable, particularly in developing country analyses, local data can be supplemented with judiciously selected data from other countries. For example, current and projected cost and performance data for some mitigation technologies (e.g.,

high-efficiency motors or combined cycle gas units) may be unavailable locally, particularly if the technologies are not presently in wide use. For this purpose, technology data from other countries can provide indicative figures and a reasonable starting point. For data on energy use patterns, such as the fraction of electricity used for motor drive in the textile industry, the use of external data can be somewhat more problematic. In general, it may be possible to use estimates and general rules of thumb

suggested by other country studies, particularly data from other countries with similar characteristics.

6. DEVELOPING SCENARIOS FOR USE IN A BOTTOM-UP ASSESSMENT

A bottom-up assessment typically compares the energy and environmental consequences of one future scenario against another. The scenarios may be composed of widely different views of the world (e.g., a rapidly growing economic world versus a slowly growing one). These types of scenarios allow companies to prepare for operations in either type of future. Often, governments though may wish to analyze the consequences of their policy or programmatic actions and in such a case it is desirable to compare a policy scenario against a reference one. The latter is often referred to as a business-as-usual or baseline scenario. Developing these scenarios is a complex process. It requires the combining of both analyses with some judgment of the future evolution of variables that are likely to affect the energy and environment system.

6.1 Developing a Baseline Scenario

Developing a baseline scenario that portrays social, demographic, and technological development over a 20- to 40-year or longer time horizon can be one of the most challenging aspects of a bottom-up analysis. The levels of projected future baseline emissions shape the amount of reductions required if a specific policy scenario target is specified and the relative impacts and desirability of specific mitigation options. For instance, if many low-cost energy efficiency improvements are adopted in the baseline scenario, this would yield lower baseline emissions and leave less room for these improvements to have an impact in a policy scenario.

Development of a baseline scenario begins with the definition of scenario characteristics (e.g., business as usual). Changes in exogenous driving variables are then specified and entered into the model, which is run to simulate overall energy use and emissions over the time horizon selected. The baseline scenario is evaluated for reasonableness and consistency and revised accordingly. Uncertainty in the evolution of the baseline scenario can be reflected through a sensitivity analysis of key parameters such as GDP growth.

The procedure will vary somewhat depending on the modeling approach used and the nature of a baseline scenario. In an optimization model, the use of different technologies is to a certain degree decided within the model, dependent on how much one wants to constrain the evolution of the baseline scenario. For example, the analyst might choose to construct a baseline scenario in which the energy supply system closely reflects or extrapolates from published plans. Alternately, the analyst might choose to give the model more flexibility to select a future energy supply system based on specific criteria. If one is using an optimization model, it is necessary to introduce certain constraints if one wishes to force the model toward a solution that approximates a business-as-usual future.

The rate of economic growth and changes in domestic energy markets are among the most important assumptions affecting projected baseline emissions. Official government GDP projections may differ from other macroeconomic projections. In terms of domestic energy markets, the removal of energy price subsidies could greatly affect fuel choice and energy efficiency, and thus baseline emissions and the impacts of mitigation options.

A preparatory step in developing a baseline scenario is to assemble available forecasts, projections, or plans. These might include national economic development plans, demographic and economic projections, sector-specific plans (e.g., expansion plans for the iron and steel industry), plans for transport and other infrastructure, studies of trends in energy use (economy wide, by sector, or by end use), plans for investments in energy facilities (electricity expansion plans, new gas pipelines, etc.), studies of resource availability, and projections of future resource prices. In short, all studies that attempt to look into a country's future—or even the future of a region—may provide useful information for the specification of a baseline scenario. However, it is unlikely that every parameter needed to complete the baseline scenario will be found in national documents or even that the documents will provide a consistent picture of a country's future. As with much of the modeling process, the judgment of the analyst in making reasonable assumptions and choices is indispensable.

6.1.1 Developing Projections of Energy Demand
In bottom-up approaches, projections of future energy demand are based on two parameters for each subsector or end use considered: a measure of the activity that drives energy demand and a measure of the energy intensity of each activity, expressed in energy units per unit of activity.

Measures of activity include data on household numbers, production of key industrial products, and demand for transport and services. Activity may be measured in aggregate terms at the sectoral level (e.g., total industrial value added, total passenger-km or ton-km) and by using indicators at the subsector level. These two measures need not be identical. For example, total industrial value added is a common indicator for aggregate activity for the industrial sector, but for specific subsectors such as steel or cement one often uses tons of production as a measure of activity. In general, physical measures of activity are preferable, but they are not appropriate in all cases (such as in light industry, where there is no aggregate measure of physical production).

In bottom-up approaches, future values for driving activities are exogenous—that is, based on external estimates or projections rather than being estimated by the model itself. Future values can be drawn from a variety of sources or estimated using various forecasting methods. Estimates of the future levels of activity or equipment ownership depend on local conditions and the behavioral and functional relationships within each sector.

Projections of the future development of energy intensities in each subsector or end use can be expressed in terms of final energy or useful energy. When the choice of end-use options is conducted within the model, however, the energy demand should be given in terms of useful energy to allow the model to select among technologies for meeting the energy requirements.

Projections should start from the base year values, such that the sum of the product of energy intensity and activity level in each subsector add up to total final or useful energy use in the base year. In energy statistics, the data are normally presented in terms of final energy. If the useful energy refers to the amount of energy required to meet particular demands for energy services. It is typically estimated by multiplying final energy consumption by the average conversion efficiency of end-use equipment (e.g., of oil-fired boilers). Applying the concept of useful energy is more difficult in the transport sector, although one can use the estimated conversion efficiency of generic engine types in various vehicle classes. If the projections are to be given in useful energy units, the statistical data should be converted using estimated base year efficiencies for each end use.

Ideally, the projections of energy intensities are based in part on historical developments. To the extent statistical data on a disaggregated level are available, they give limited information for economies that have undergone significant structural changes or changes in taxation/subsidies on energy. Even if reliable historical data are available, assumptions on the development of the energy intensities have to be made using careful judgment about the status of existing end-use technologies and future efficiency improvements that should be included in the projections.

It is important to distinguish between improvements included in the exogenous demand projections and improvements that are explicitly included as technology options in the model. For example, future improvements of building insulation standards can either be directly included in the demand projections as an improvement of intensity for space heating or modeled as technology options that can be chosen individually in the assessment, depending on their attractiveness in the different scenarios. The distinction is especially important in optimization models. One can assume that the insulation standards will be implemented (e.g., through use of regulations) or allow the model to choose the implementation. In the latter case, the insulation option will be implemented if its cost is less than the cost of supplying the heat using available options for space heating.

Once the initial baseline scenario is prepared, it is reviewed to assess whether it presents a comprehensive and plausible future for the country in light of real-world constraints. Some specific questions might include the following:

- Can the indicated growth rates in energy demand be sustained over the study period? Is it a reasonable rate, given recent experience in the country and region?
- Is the level of capital investment needed to sustain the indicated levels of industrial growth likely to be forthcoming?
- Will the country be able to afford the bill for fuel imports that is implied by the baseline scenario?
- Will the capital investment needed for energy supply system expansion be available, given competition for limited financial resources?
- Is the indicated increase in transportation use plausible, given current and planned transportation infrastructure?
- Are the emission factors in use appropriate for future technologies?

Answers to these types of questions might indicate the need for adjustments to the baseline scenario or sensitivity analyses of key parameters.

6.2 Developing Policy Scenarios

The process of developing a policy scenario or scenarios involves establishing a scenario objective and combining specific options in an integrated scenario. Integrated scenario analysis is essential for developing accurate and internally consistent estimates of overall cost and emissions impacts since the actual emissions reduction from employing a specific option can depend on the other options included in a scenario. For instance, the level of reduction in GHG emission associated with an option that saves electricity is dependent on the electricity generation resources whose use would be avoided (e.g., coal, oil, hydro, or a mix). In reality, the type of electricity generation that the efficiency option would avoid will change over time, and, if lower GHG emitting electricity resources are also introduced in the scenario, the GHG savings of the efficiency option may be reduced. Integrated scenario analyses are intended to capture these and other interactive effects.

Where using an optimization model, the difference in input data for the baseline scenario and the policy scenario(s) is typically less than in an accounting model, where the choice of technologies is exogenous to the model. An optimization model chooses from the whole set of available technologies to satisfy the given constraints.

6.2.1 Objectives for a Policy Scenario

Several objectives are possible for designing a policy scenario. The objective depends on political and practical considerations. Types of objectives include the following:

- *Emission reduction targets.* For example: 12.5% reduction in CO_2 emissions by 2010, and 25% reduction by 2030, from baseline levels. An alternative is to specify reductions from base year levels, which avoids making the amount of reduction dependent on the specification of the baseline scenario.
- *Identification of options up to a certain cost per ton of energy or emissions reduction.* The energy or emissions reduction given by the resulting technology mix would reflect the level of reduction that could be achieved at a certain marginal cost.
- *No-regrets scenario.* This scenario is a common variant of the previous type of objective, where the screening threshold is essentially zero cost per tonne of energy or GHG reduced.

- *Specific technology options or packages of options.* Examples of this type of scenario might be a natural gas scenario, a renewable energy scenario, or a nuclear scenario.

7. RESULTS FROM A BOTTOM-UP APPROACH

Following are some key questions that an analyst would seek to answer from a bottom-up energy sector assessment:

1. What is the economic cost of providing energy services in a baseline or policy scenario? What is the incremental cost between scenarios?
1a. What are the capital and foreign exchange implications of pursuing alternative scenarios?
2. What is the economic cost of pursuing particular mitigation (policy and technology) options, such as high efficiency lighting or a renewable technology, and what are its local and global environmental implications?
3. What are the costs of reducing emissions to a predetermined target level? (Target may be annual or cumulative).
4. What is the shape of the marginal cost curve for reducing carbon emissions?
4a. How do alternative technologies rank in terms of their carbon abatement potential?

Any one of the three types—accounting, optimization, and iterative equilibrium—of models discussed here can address questions 1 and 2. Question 1a is important for developing country planners, since these two cost components are often insufficient in these countries.

Question 3 is easiest to address using an optimization model. Question 4 requires that energy supply and demand be evaluated in an integrated manner. A demand-side mitigation measure may change the energy supply configuration measure, which will affect the GHG emissions of the energy system. The optimization and iterative models are capable of capturing the integrated effect and deriving the changes in environmental emissions. The accounting models may not capture the changes in the energy supply mix and the consequent GHG emissions and thus may show higher emissions reduction for a mitigation measure. Only the optimization models can calculate marginal costs directly. In the other models, an approximation of the marginal cost curve can be constructed by performing a large number of carefully selected runs.

SEE ALSO THE FOLLOWING ARTICLES

Economics of Energy Demand • *Economics of Energy Supply* • *Modeling Energy Markets and Climate Change Policy* • *Modeling Energy Supply and Demand: A Comparison of Approaches* • *Multicriteria Analysis of Energy* • *National Energy Modeling Systems*

Further Reading

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